Demonstration of a High-Brightness Water-Window Laser-Plasma Source for Soft X-Ray Microscopy

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Demonstration of a high-brightness water-window laser-plasma source for soft x-ray microscopy

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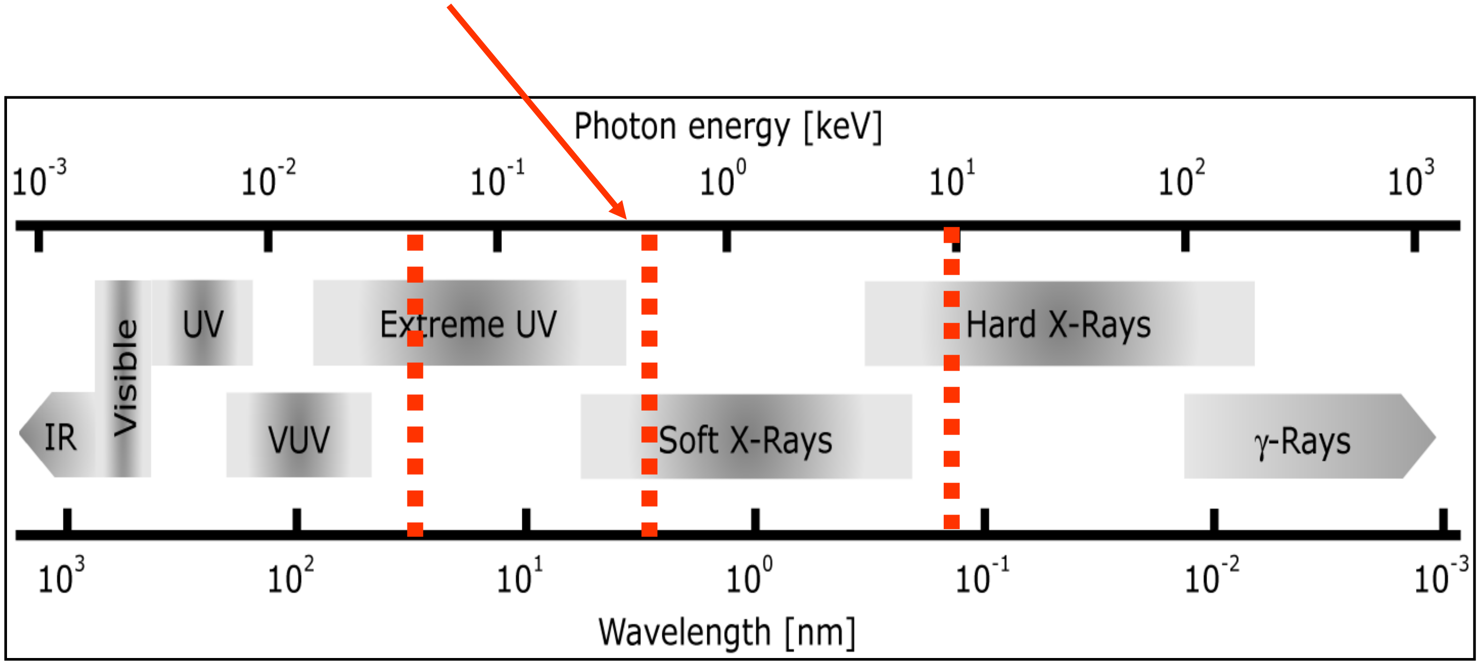
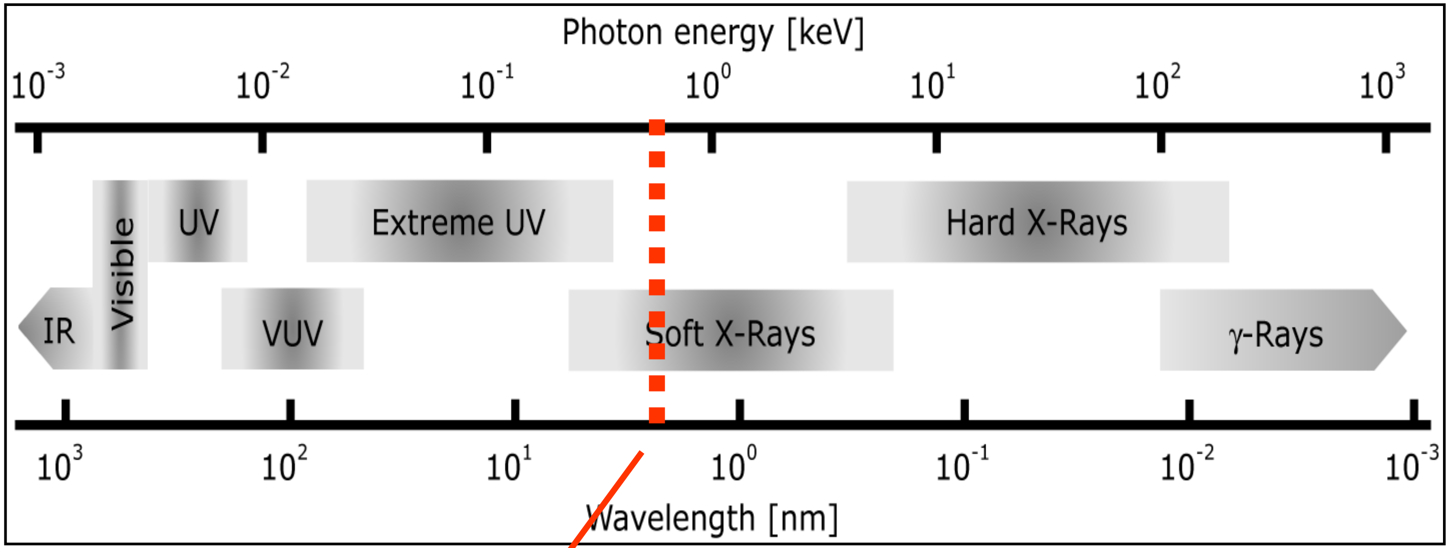
Today

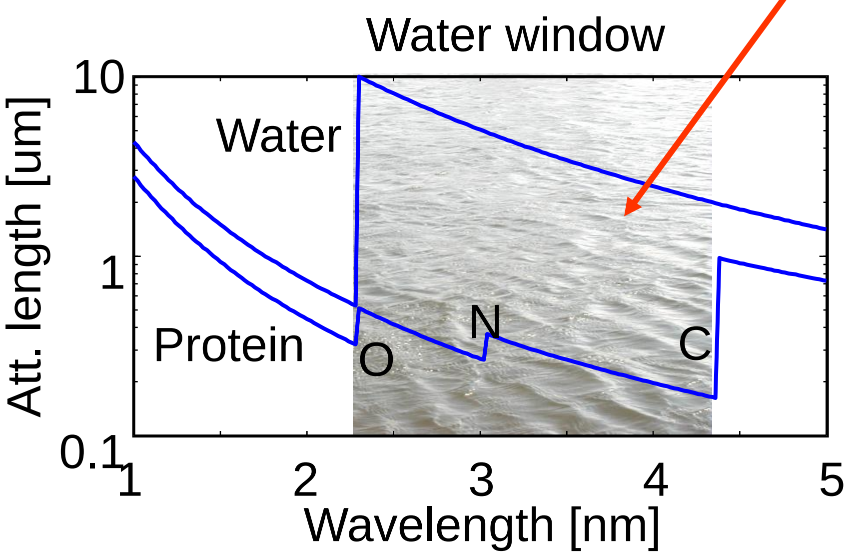
<u>Soft x-rays :</u>

Liquid-jet laser-plasma sources
x-ray optics
Laboratory x-ray microscopy



Soft x-rays:
Water-window x-ray microscopy

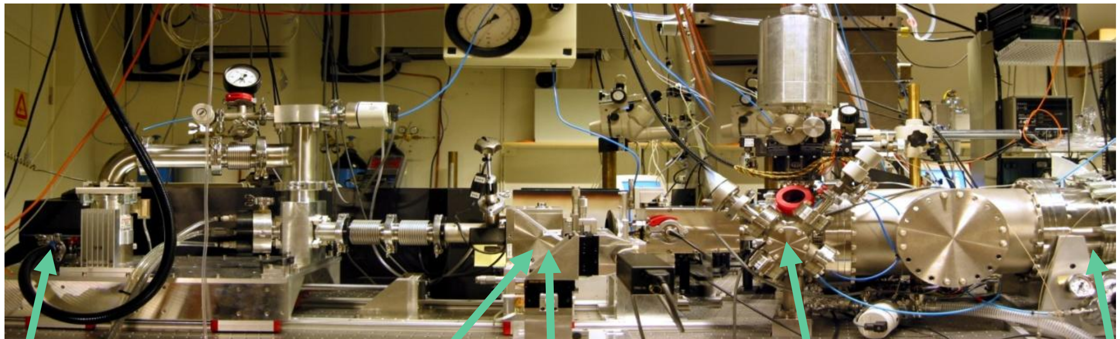




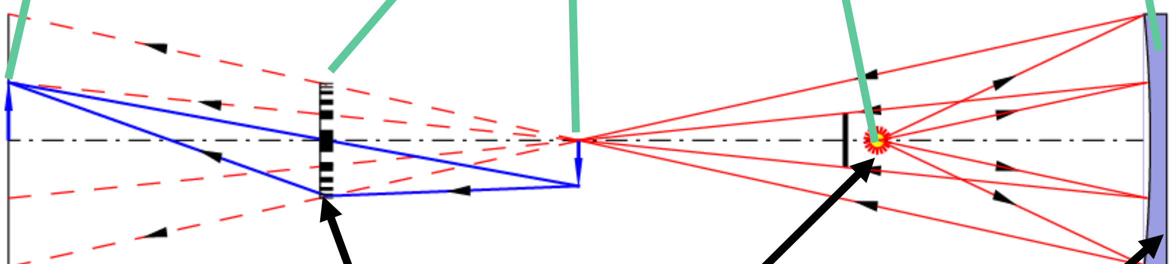
+ Resolution: 0.61λ/NA
+ Natural contrast for wet/frozen specimen
+ Possibility to study thick (~10 μm) objects
- Lack of laboratory high-brightness sources
- Inefficient optics

Soft x-rays:

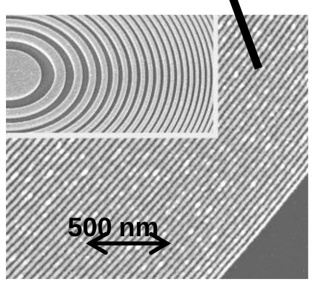
Laboratory water-window x-ray microscopy

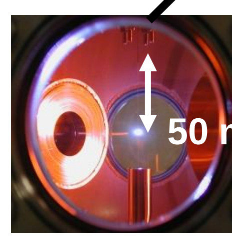


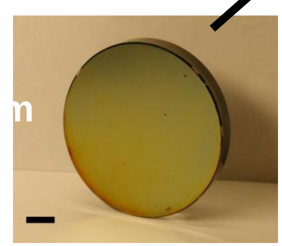
λ=3.37 nm &
λ=2.48 nm



Micro zone plates for high-resolution imaging





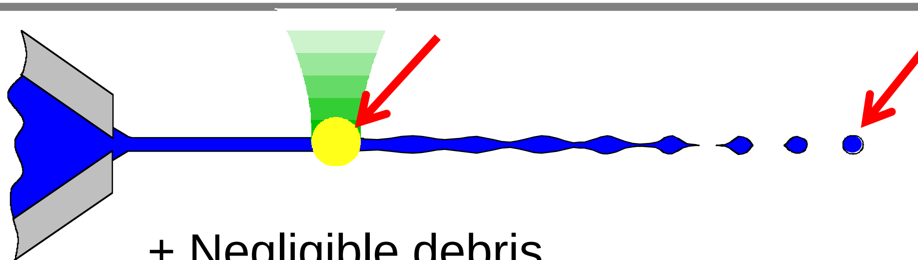


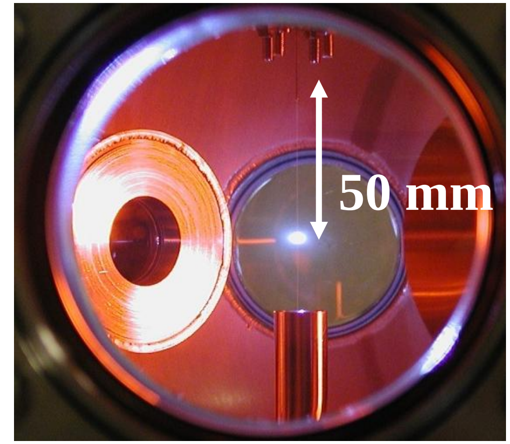
Normal-incidence multilayer mirrors as condensors

Berglund et al, J. Microsc. (2000), Johansson et al, RSI (2002) Takman et al, J. Microsc. (2007)

Laboratory soft x-ray sources:

Liquid-jet/droplet laser plasmas

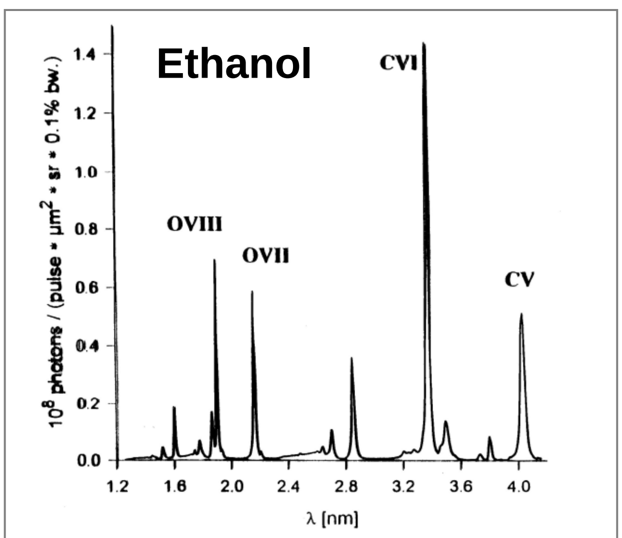




+ Negligible debris
+ Regenerative target
+ High rep.-rate operation
+ High-power operation possible
+ Tailored spectral emission

Rymell et al, Opt. Commun. (1993); Malmqvist et al, RSI (1996)

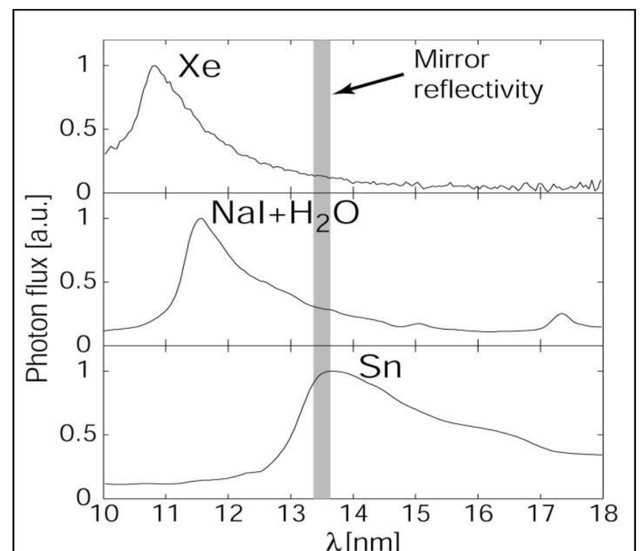
$\lambda \approx$2-4 nm: Water-window



+ Line emission ⇒ fixed wavelength
+ $\lambda/\Delta\lambda$>500
+ High brightness

Rymell et al, APL (1995), Berglund et al APL (1997)

λ=13 nm: EUV Lithography

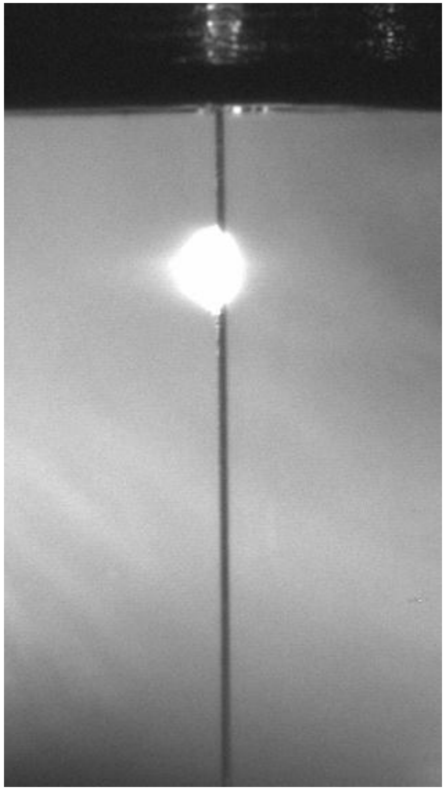


Hansson et al, MNE (2001) ; Jansson et al APL (2004)

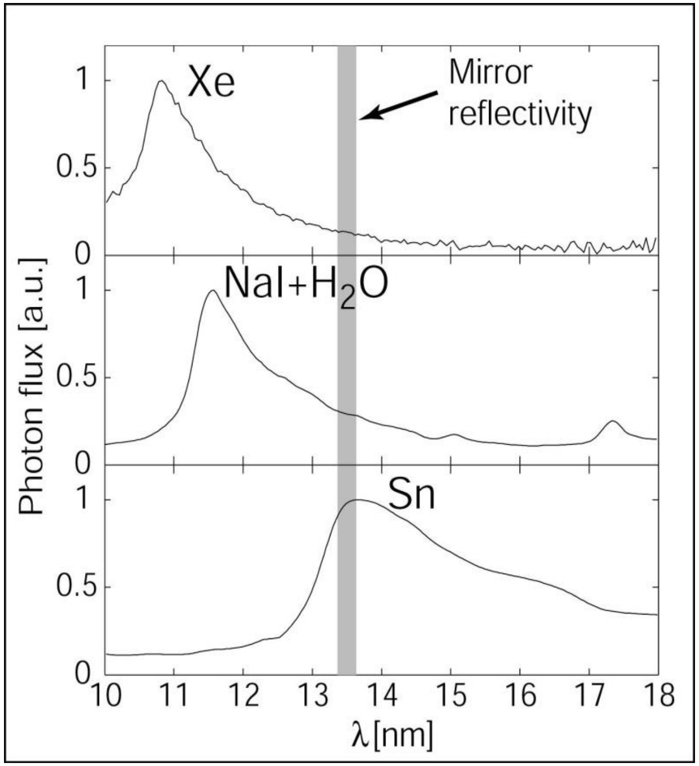
EUV sources:

Liquid tin jet

Stable jet @ >250 C



Spectral match



CE: 2.5% into (2%BW×2π×sr)

Debris:

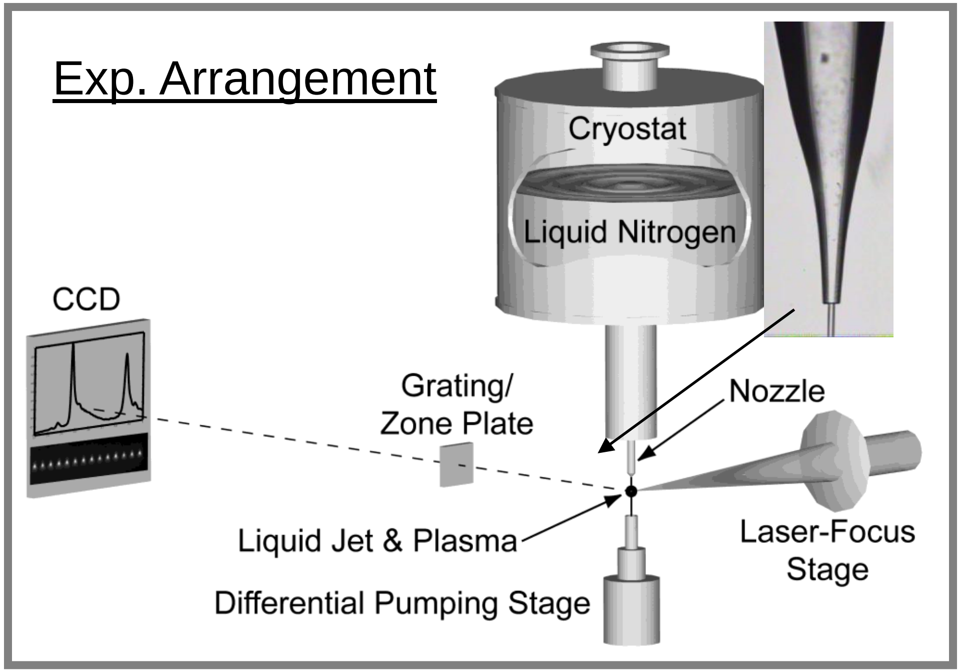
1 h gave coating

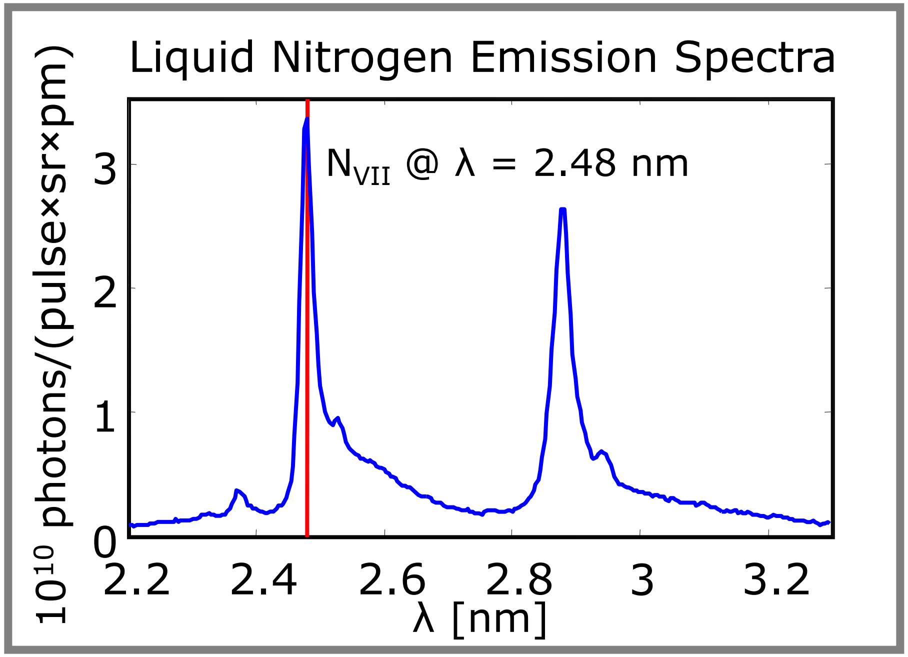
Mitigation need: ~10^8

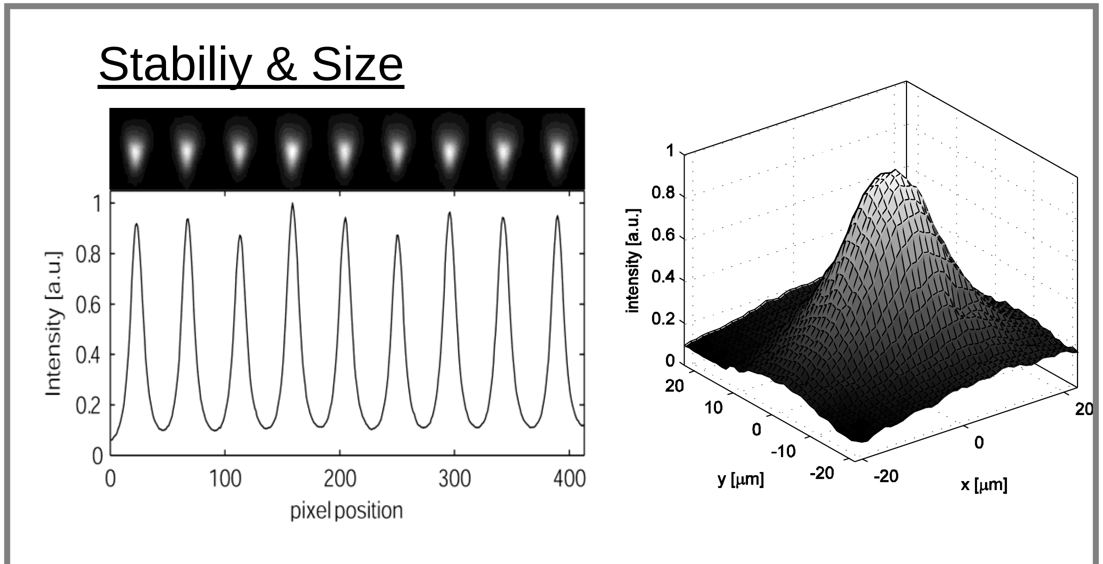
Jansson et al . Appl. Phys. Lett. (2004)

Water window sources:

The liquid-nitrogen-jet source







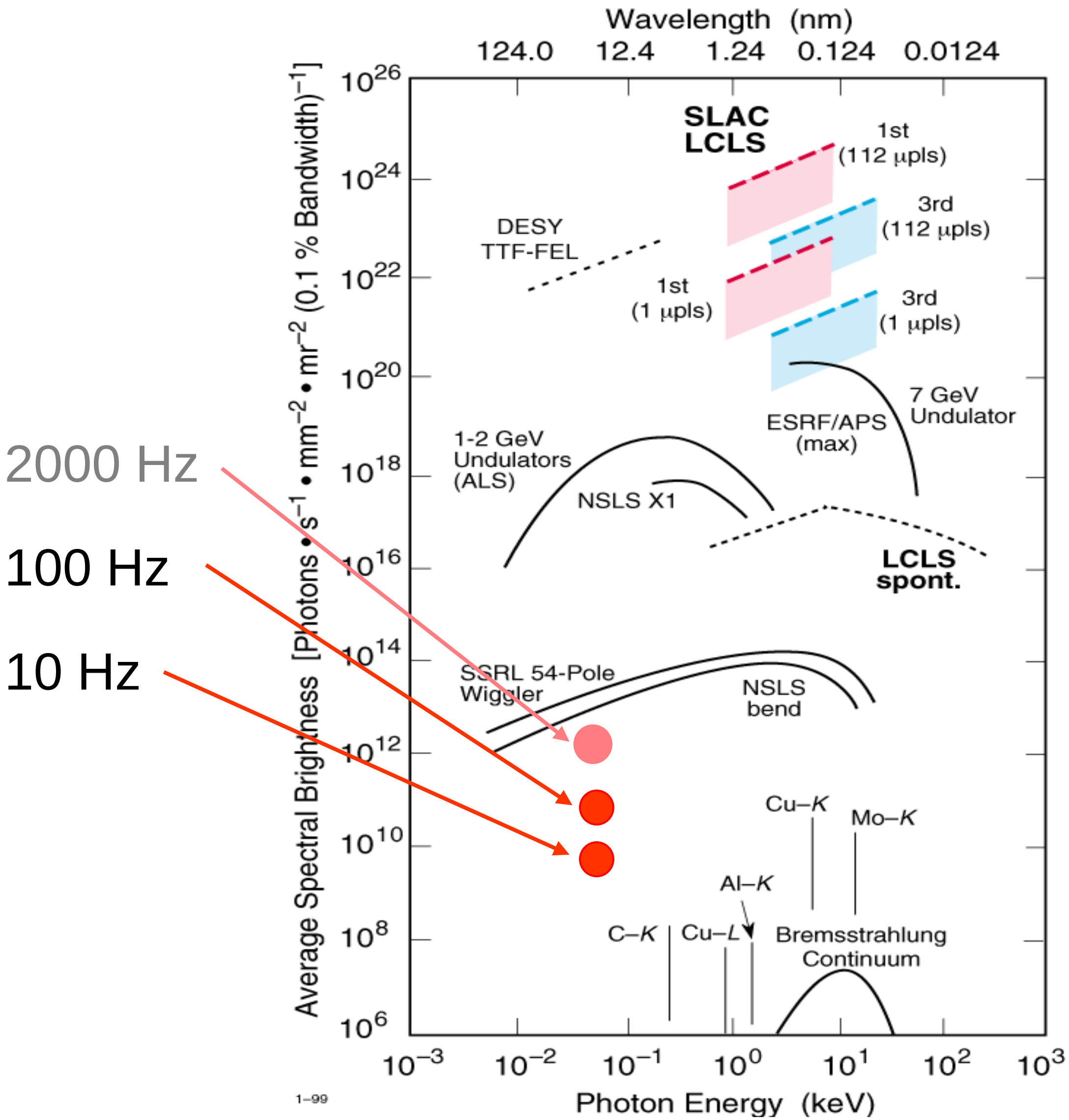
Laser: 20W, 100 Hz, 3ns

Flux: 1×10^{12} ph/pulse×sr×line
Stability: ±2 μm
Brightness: 4×10^{8} photons/(pulse×sr×μm²×line)
Illumination Uniformity:10%

Berglund et al, RSI (1998), Jansson et al RSI (2005)

Liquid-jet laser-plasma sources:

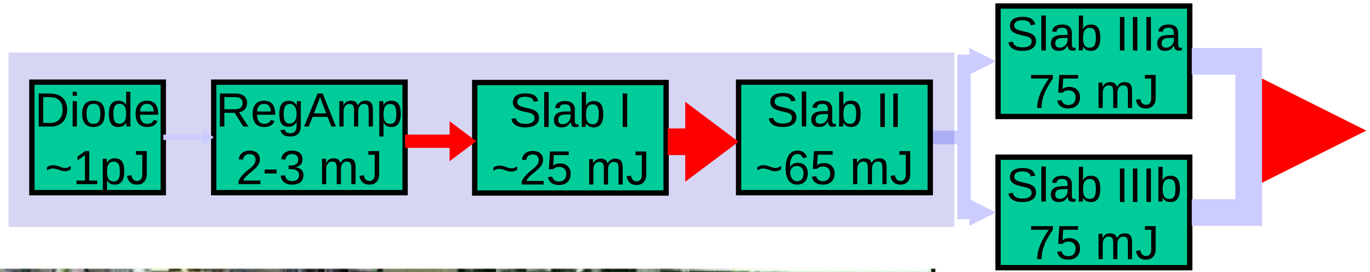
Brightness

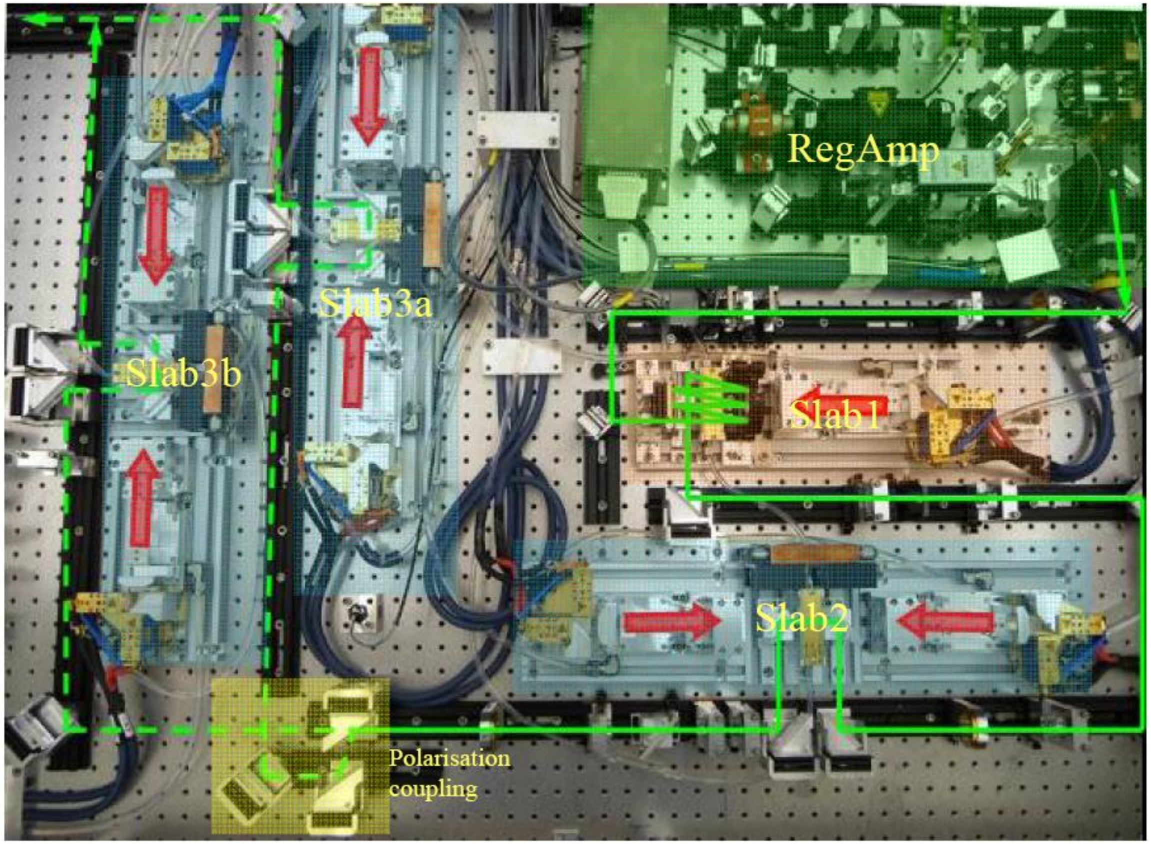


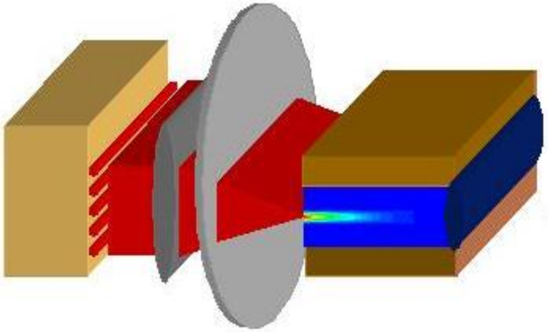
Bright,
but not like a synchrotron

Next-generation liquid-jet laser plasmas:

320 W, ~600 ps, 2 KHz Nd:YAG Slab

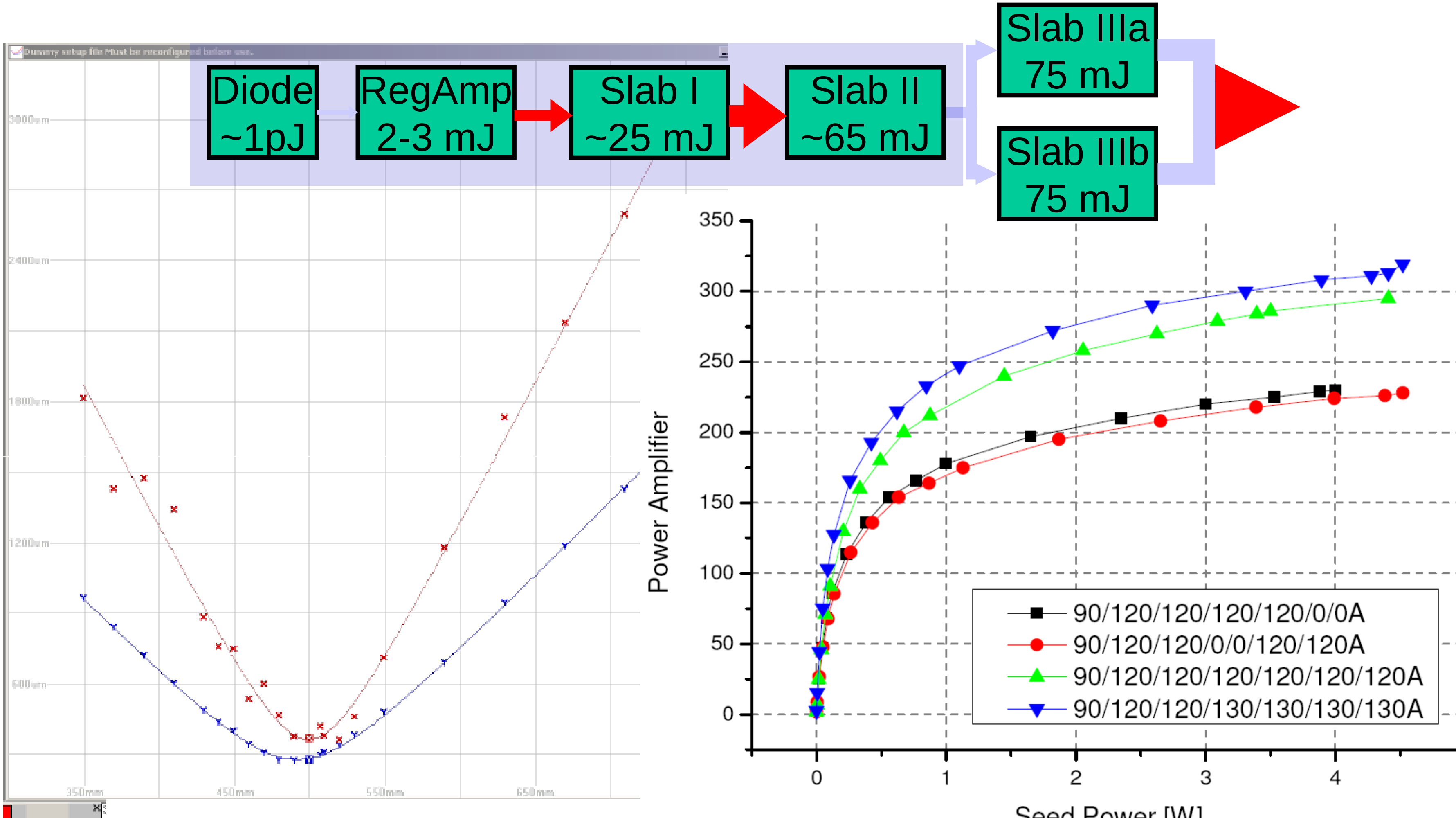






Thanks to D. Esser, M Hofer et al, FhG ILT, Aachen

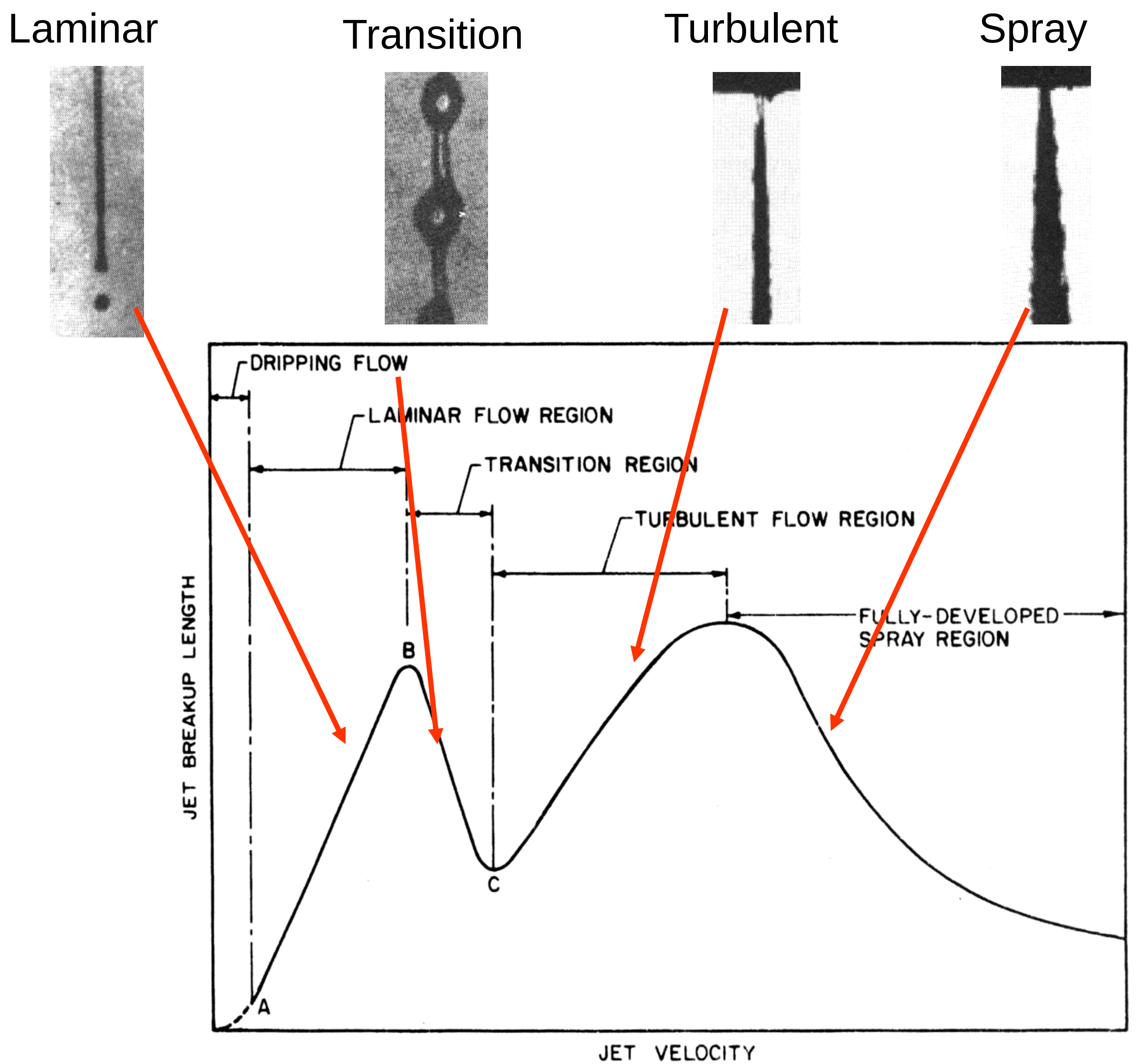
Laser Performance



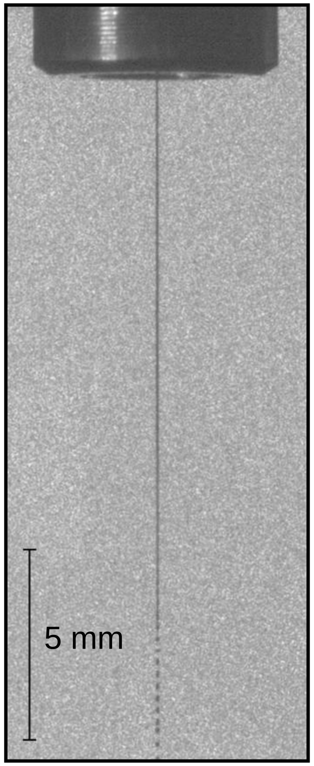
M^2Fast = ~ 1.3 **M^2Slow = ~ 3.3**

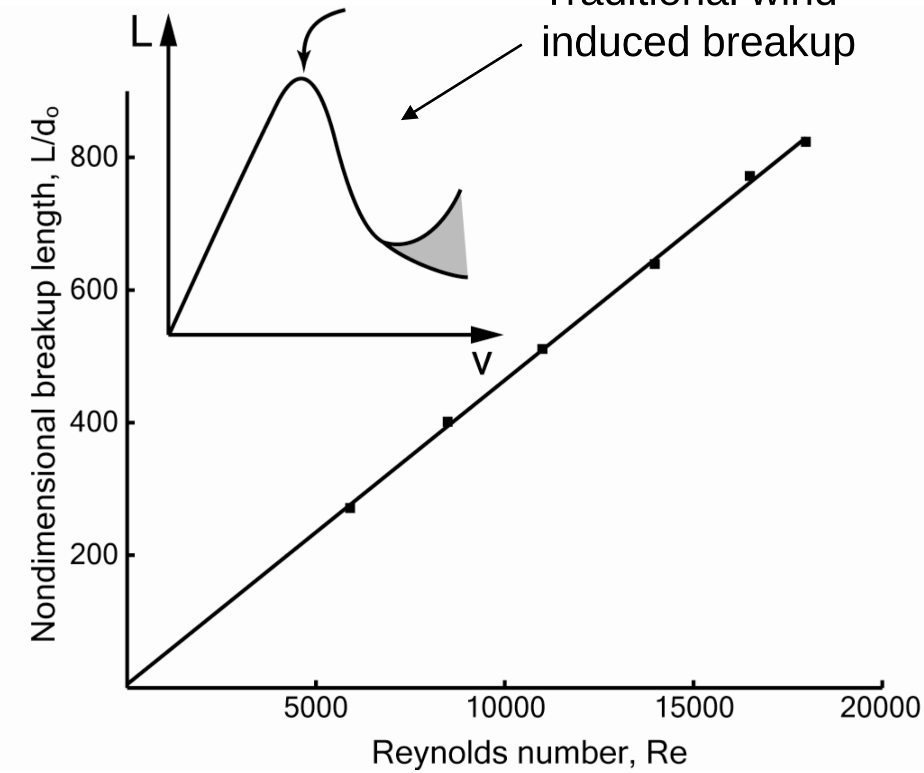
Source scaling to higher power:

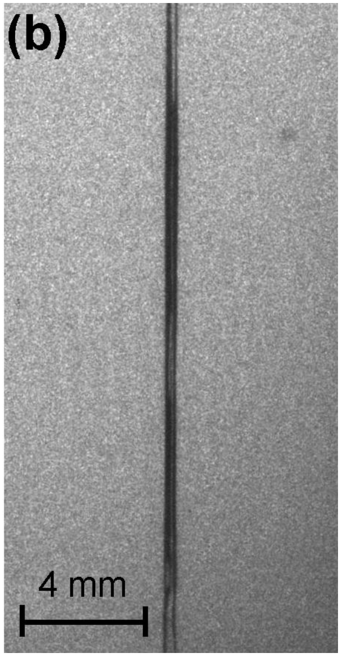
Jet Stability



Source scaling:
Higher jet speed







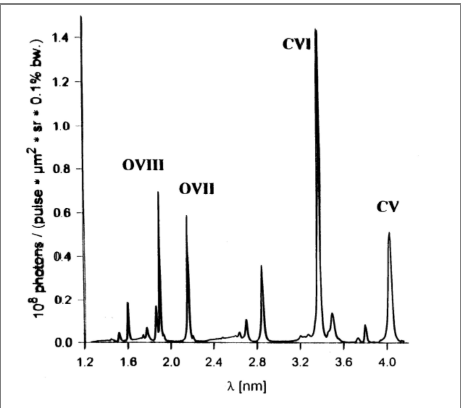
Dynamic similarity experiments with water show that a 30 μm, 500 m/s (Re=56000) liquid-tin jet operates stably in vacuum

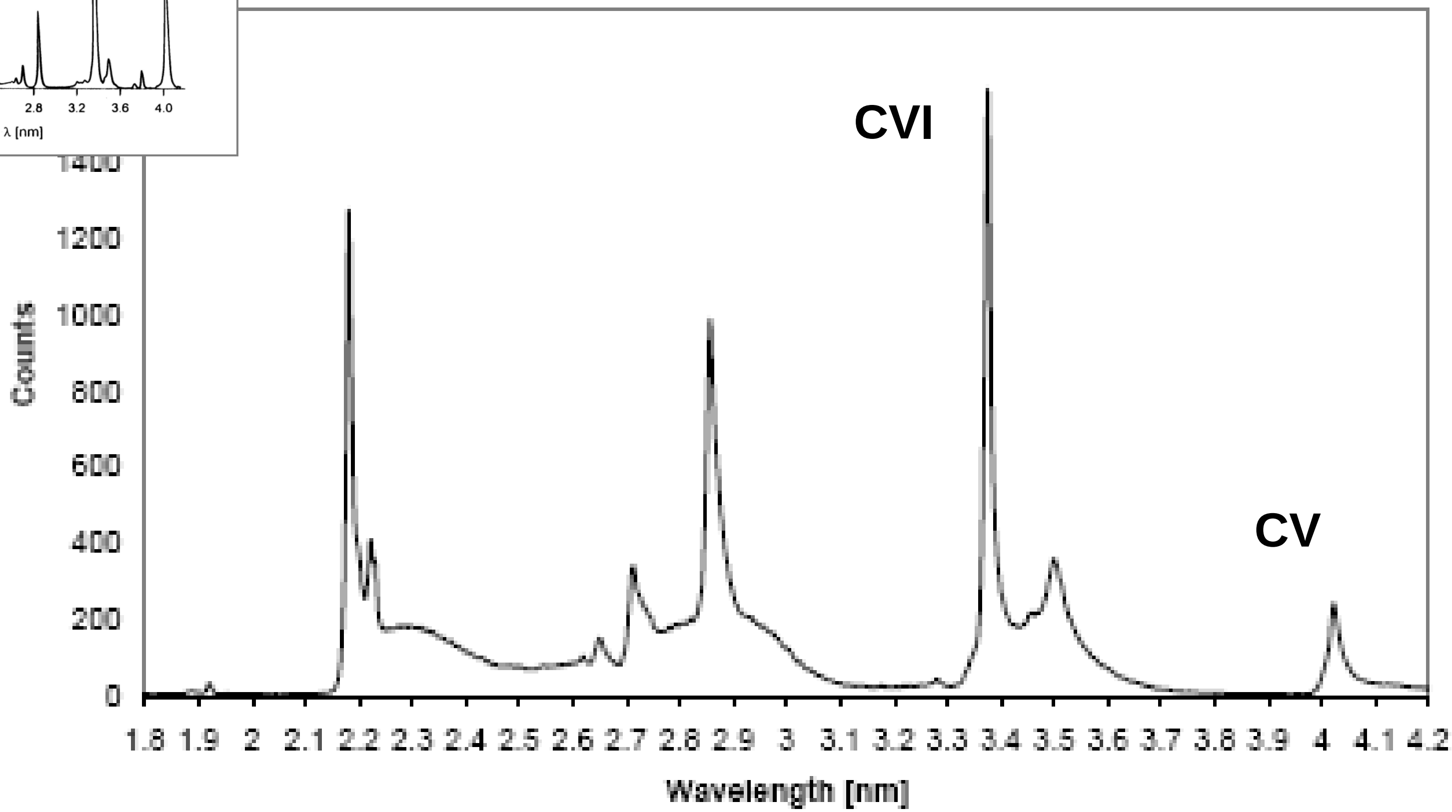
Stable operation of tin jet to Re=18000
(diam=75 μm, v=60 m/s)

Otendal et al, Exp. Fluids (2005)

First methanol-jet spectrum

220 W, 0.8 ns, 2 kHz

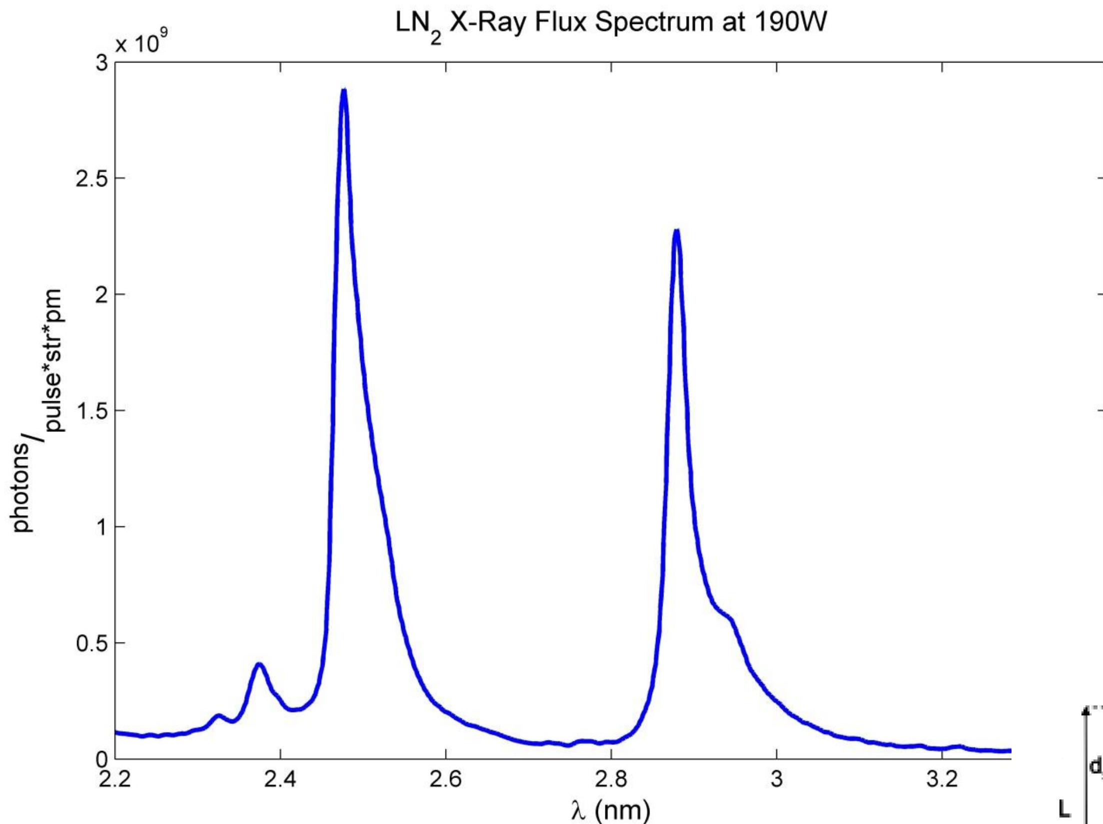




Jet is stable
Hot plasma

Martz et al, in progress,

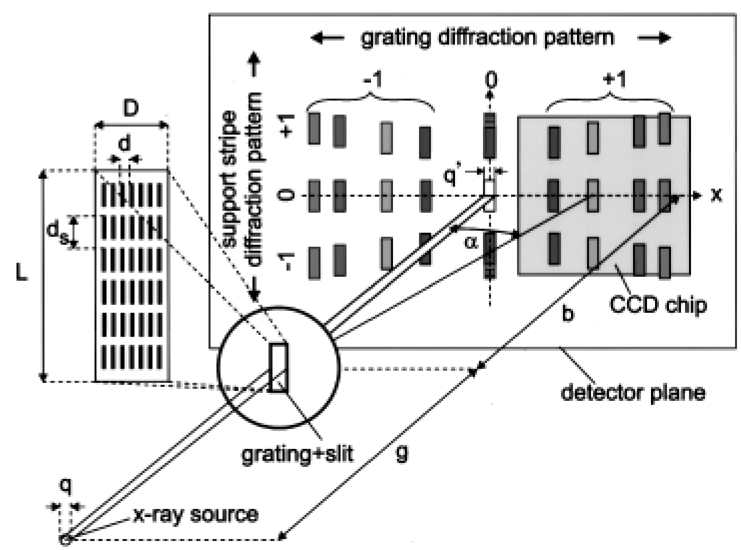
LN_2 Bright Spectrum



Martz et al, in progress,

Geometric Resolution Limit
$\Delta\lambda = 0.022$ nm

$\lambda/\Delta\lambda$ at least 700*



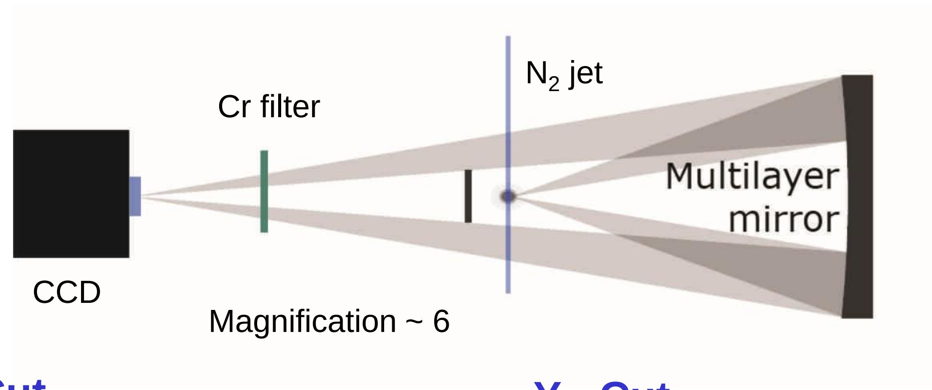
CCD & Grating detection calibrated with the Max-Born Institute @ BESSY

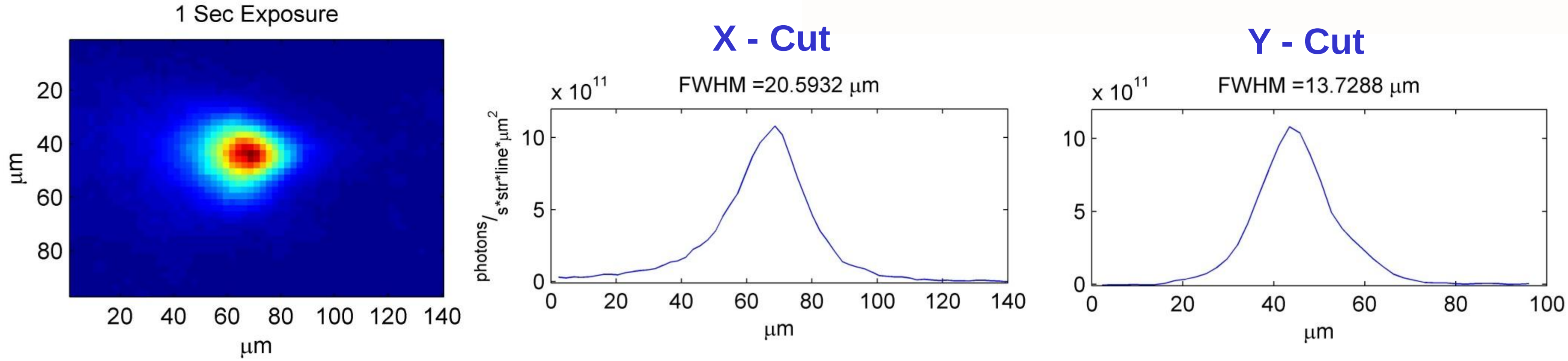
*T. Wilhein et al, Appl. Phys. Lett. **71**, 190 (1997)

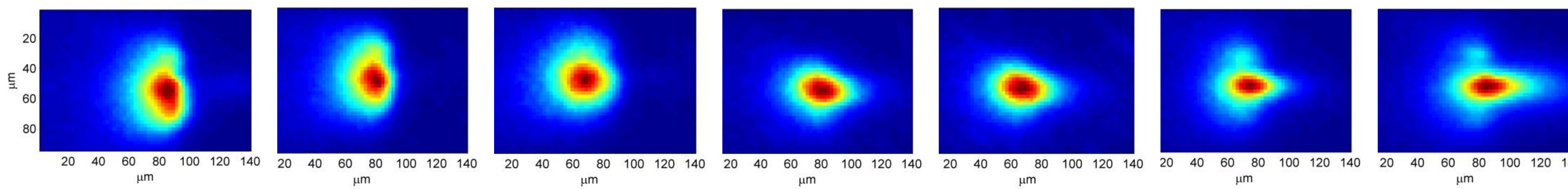
T. Wilhein et al, Rev. Sci. Instrum. **70**, 1694 (1999)

Laser Plasma Brightness

$$\underline{\mathbf{0.5 - 1.5 \times 10^{12}}} \frac{\text{photons}}{\text{sec x str x line x } \mu m^2}$$

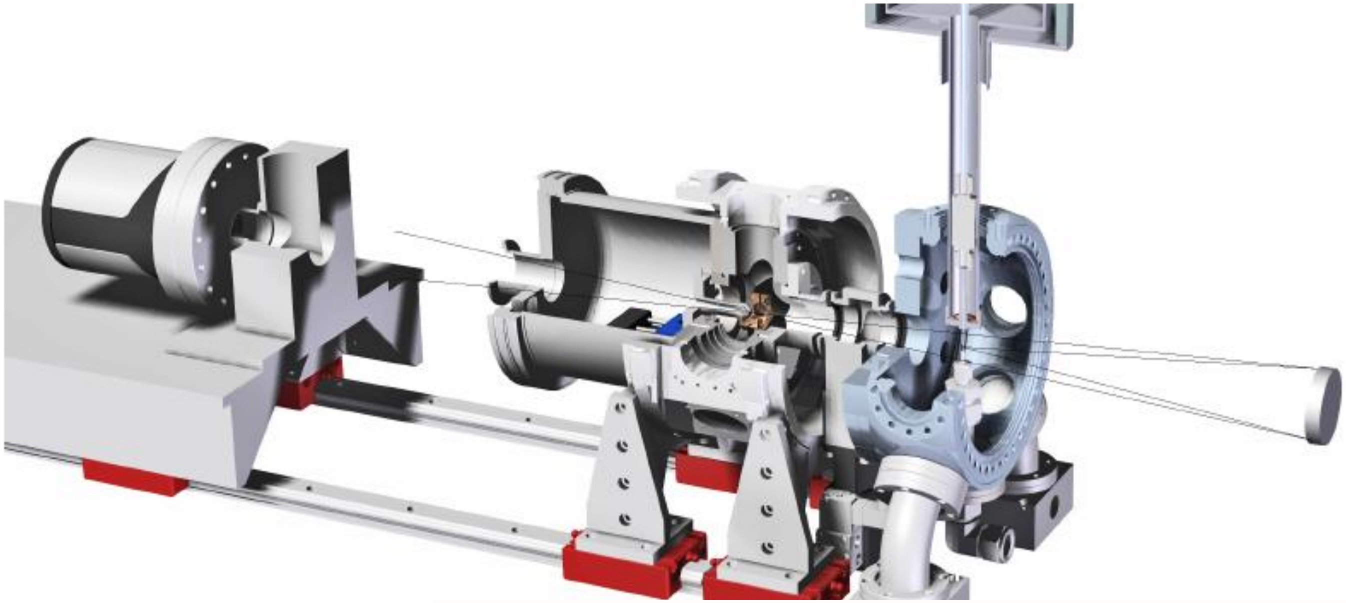


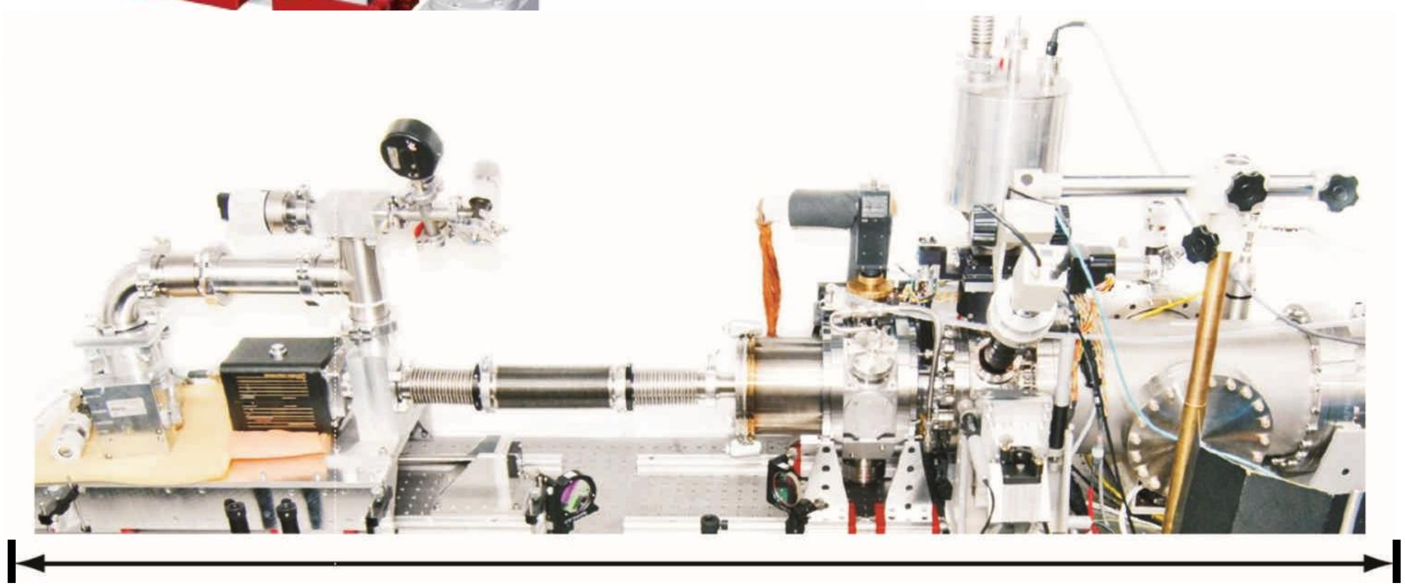




Martz et al, in progress,

Soft X-Ray Microscope



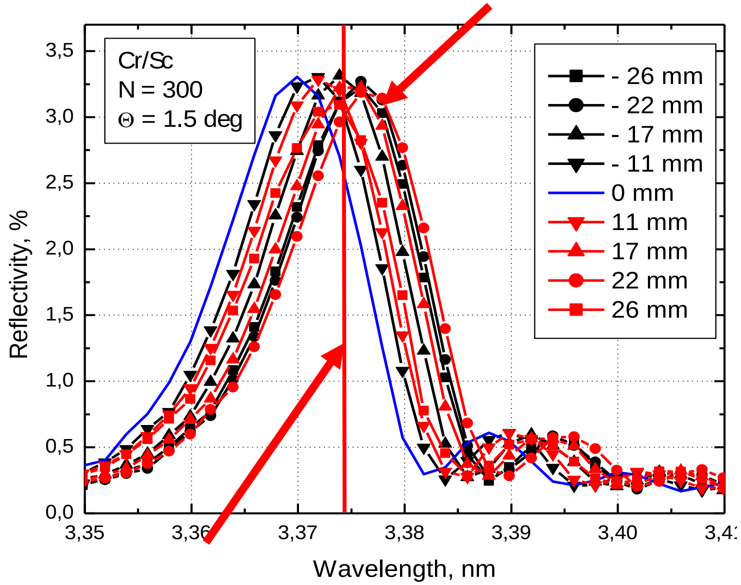


Soft x-ray optics:

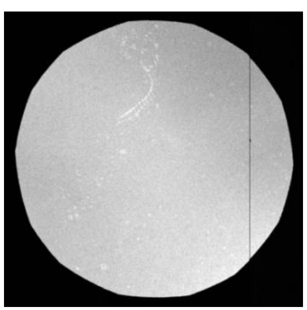
Normal-incidence multilayer condensers

Uniformity: Cr/Sc @ 3.374 nm

Refl. >3%!



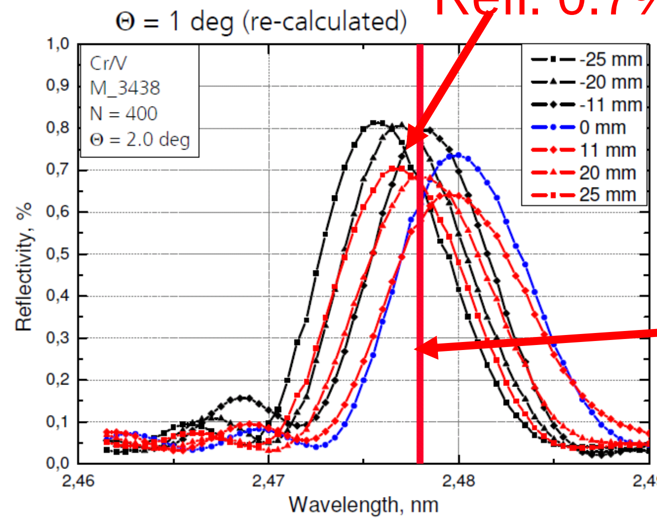
λ=3.374 nm



Stollberg et al, RSI (2007)

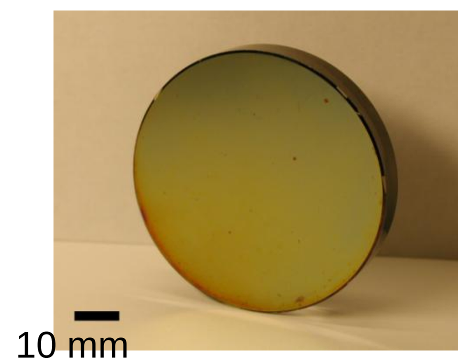
Uniformity: Cr/V@ 2.48 nm

Refl. 0.7%



λ=2.478 nm

- Cr/Sc
- 58 mm diam
  (active from 20mm - 58mm)
- 350 mm radius
- 200 bilayers
- $\lambda/\Delta\lambda \approx 300$
- Good uniformity
- Good λ match

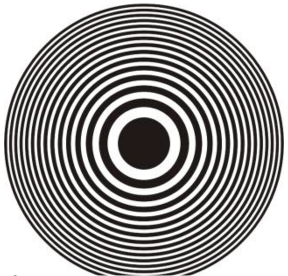


Thanks to S. Yulin, FhG Jena

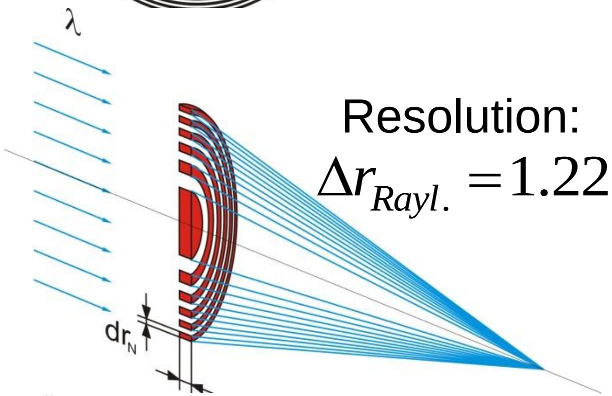
Soft x-ray optics:

Zone plates

Basics

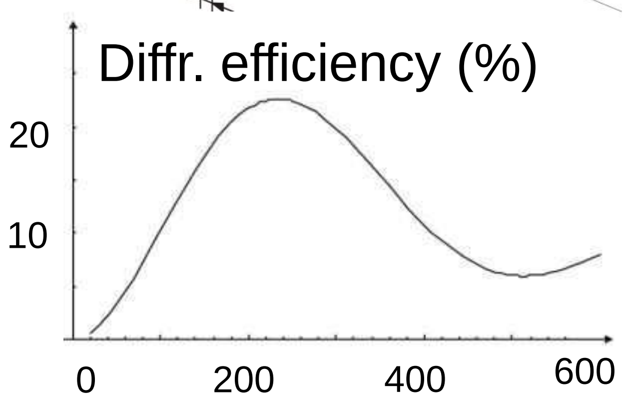


Circular diffraction gratings



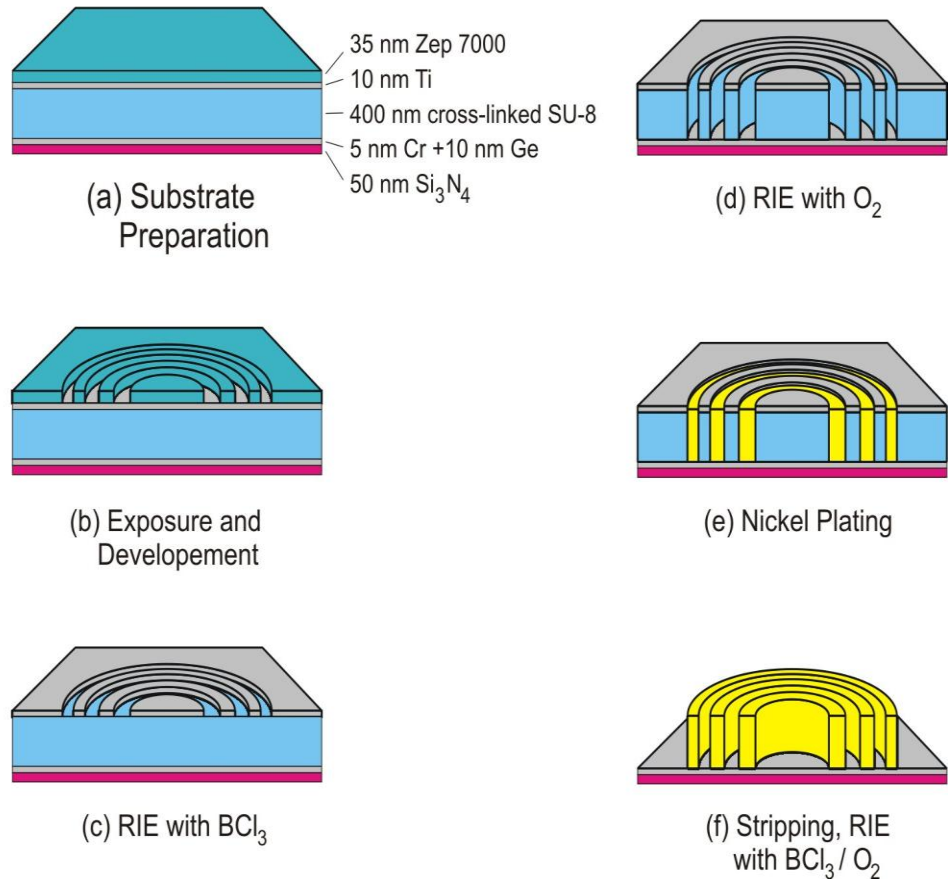
Resolution:

$$\Delta r_{Rayl.} = 1.22 dr_N$$



Nano-fab process for Ni zone plates

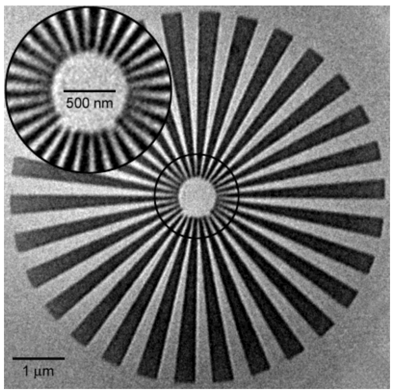
@ Albanova Nanofab Lab

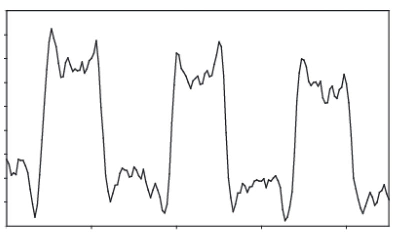


Holmberg et al, MNE (2003),

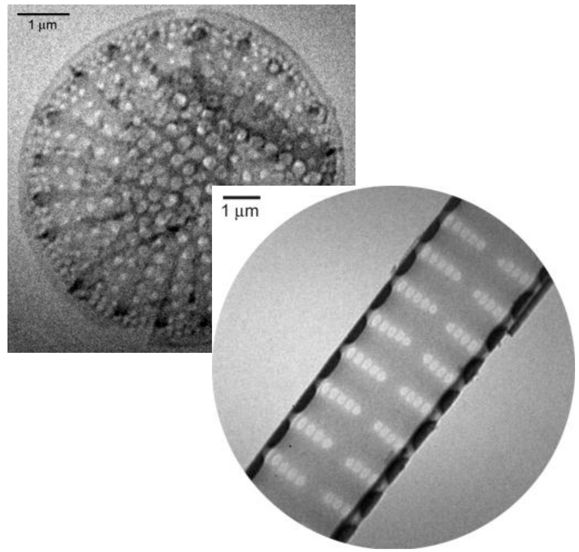
Laboratory water-window x-ray microscopy

Test patterns:

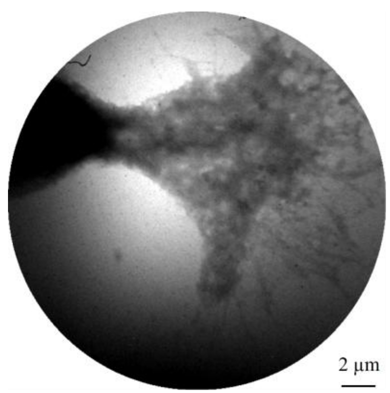




Diatoms:

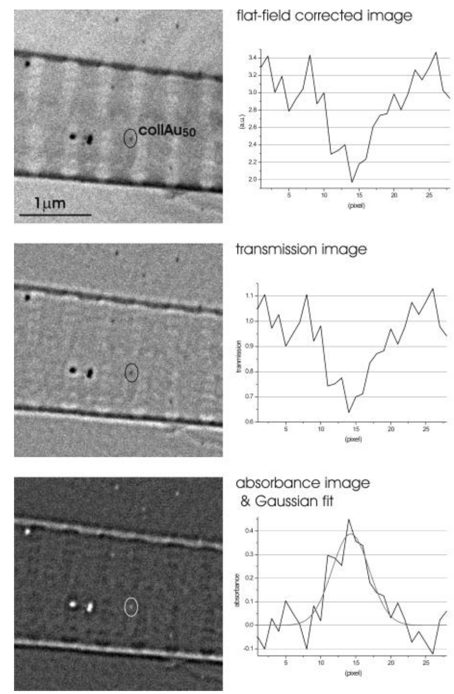


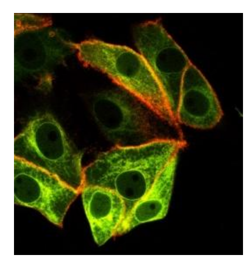
COS-7 cells



Function:

Size-selective coll.
Au identification





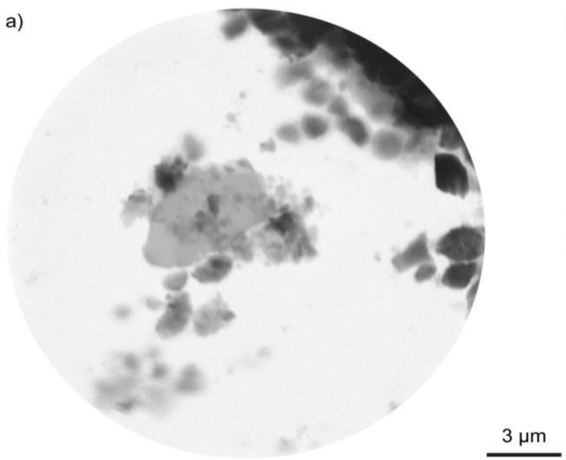
Goal: protein co-localization

Takman et al, J. Microsc. (2007), v. Hofsten et al, Ultramicr (2007) Stollberg et al, J Micr. (2006); Stollberg et al, J Micr. (2007); Thieme et al, J. Phys. C (2009)

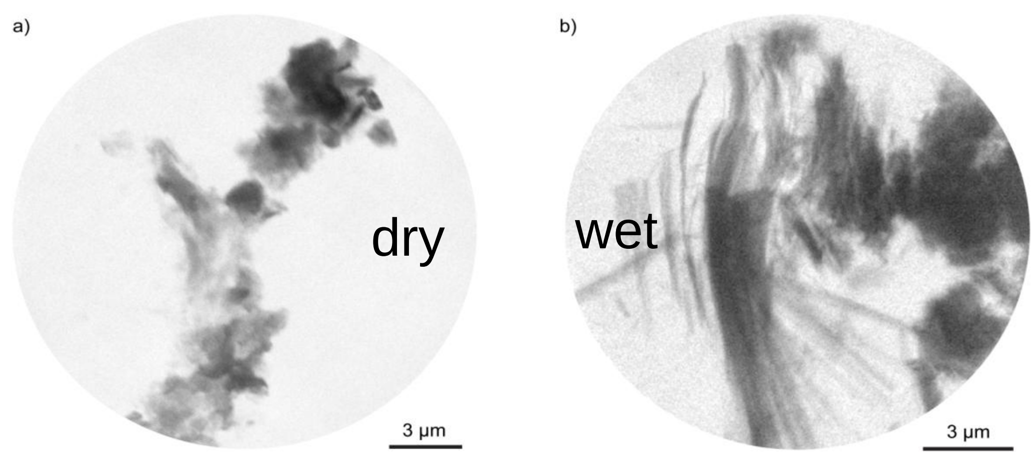
Recent results:

Environmental colloids

Chernozem, wet



Nontronite



Thanks to J Thieme et al.!

Hertz et al, submitted Chem Geol (2010)

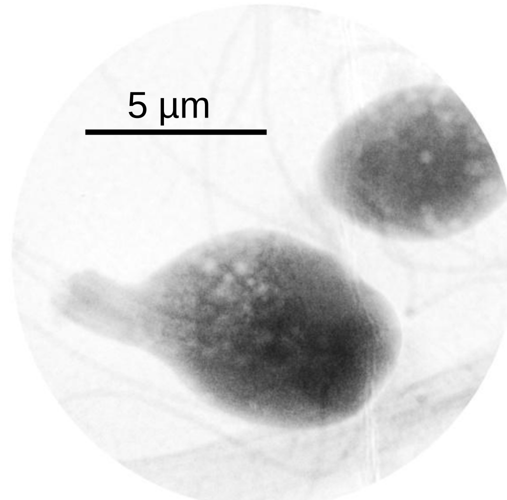
Recent results:

Parasites and cells

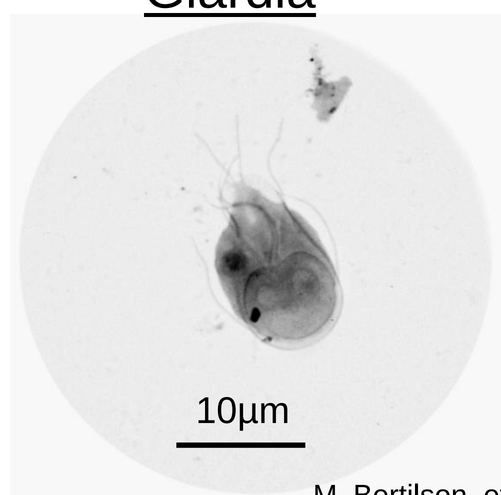
Cryo fixation:

Hydrated samples on TEM grids
Plunge-freeze in liquid ethane (-180 °C)
TEM high-tilt cryo sample holder

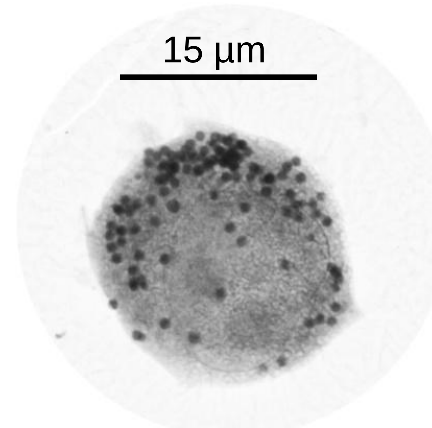
Spironucleus

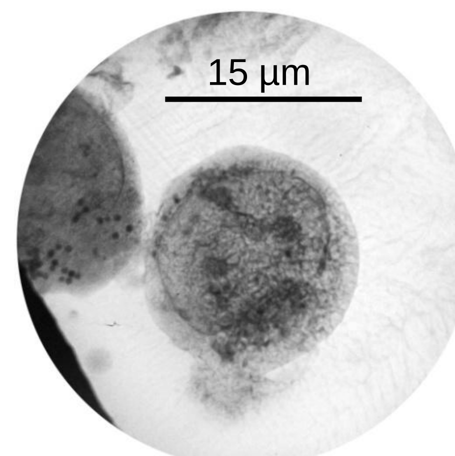


Giardia



Human immune system B-cells





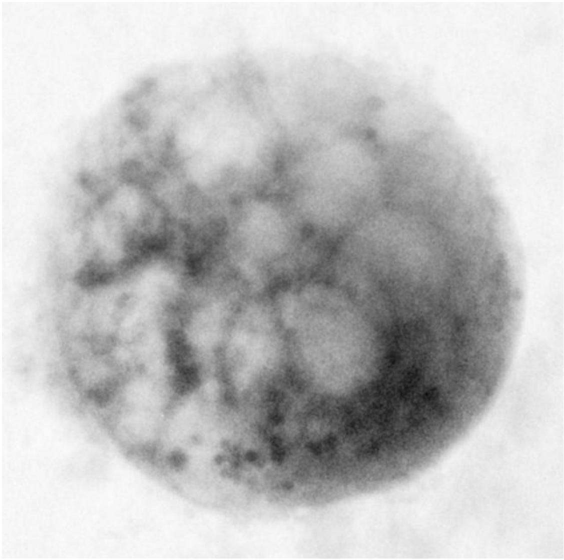
M. Bertilson, et al, Opt. Lett. Vol. **36**, 2728-2730 (2011)

Thanks to J Jerlström and S Svärd !

Recent results:

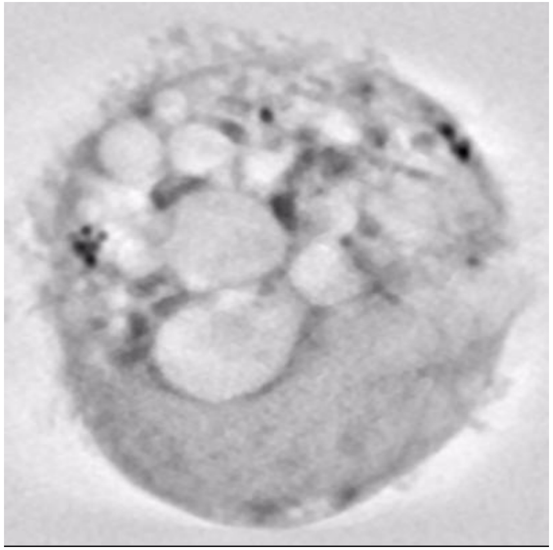
Laboratory Cryo Tomography: Human kidney cell

2D image

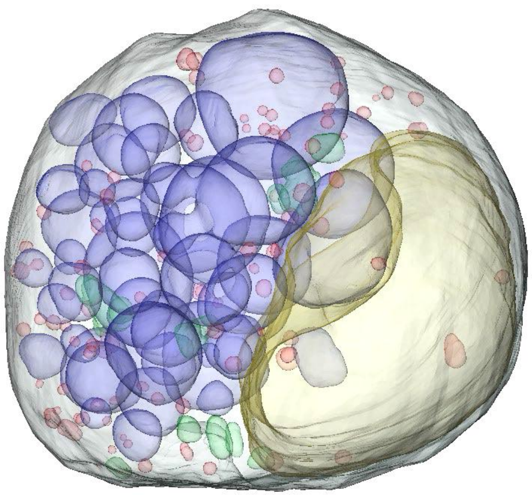


13 µm

Reconstructed volume



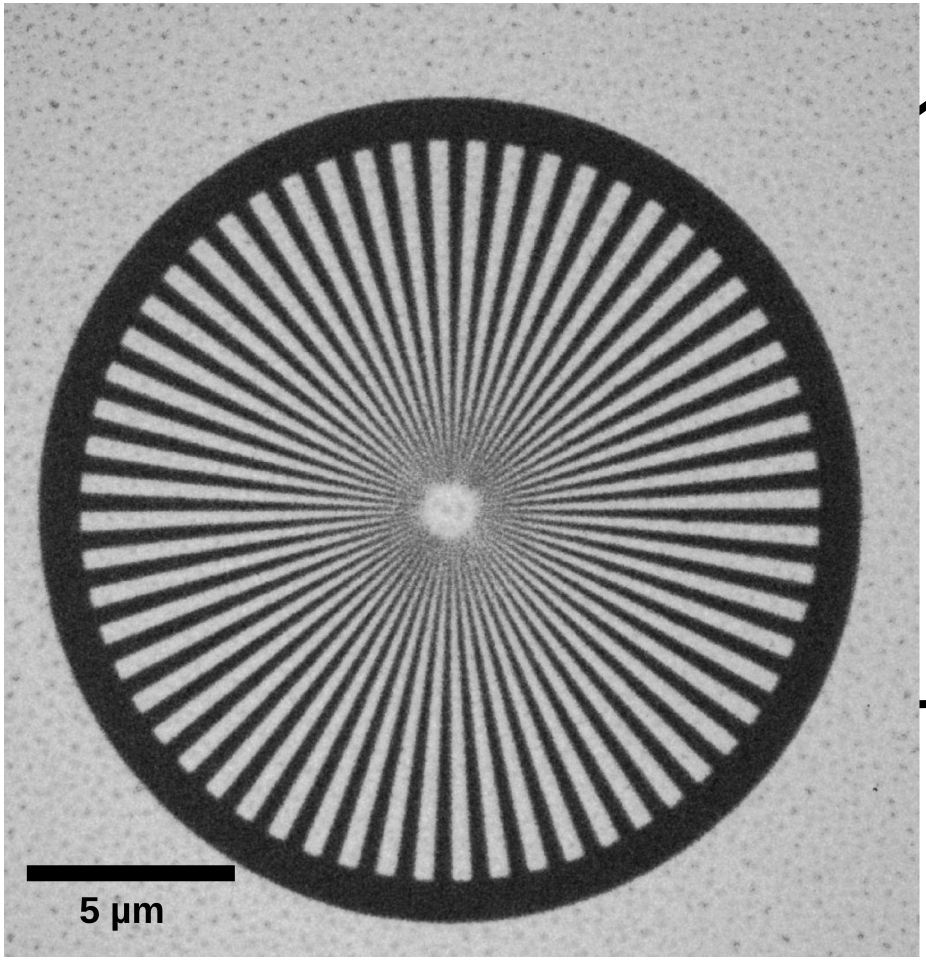
Surface rendering

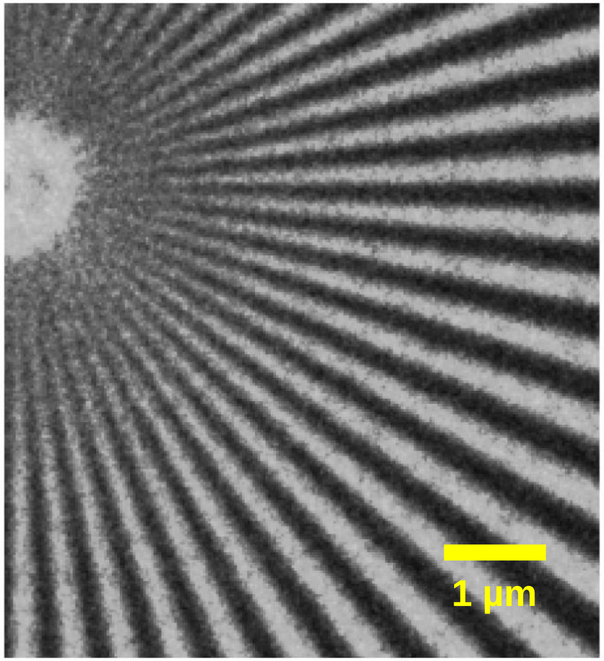


- Tilt series: ±44°, 58 images, 120 s/exp.
- Alignment using landmarks
- Reconstruction with SIRT
- Semi-manual segmentation based on local abs coeff.

M. Bertilson, et al, Opt. Lett. Vol. **36**, 2728-2730 (2011)

10 sec Exposure





Resolution approaching the limit of the ZonePlate (~ 40 nm)

Challenges

- Maintaining Focus Quality
  - Stable Laser System is Key
  - Use Appropriate Materials

- Minimize Heating of Jet

- Minimize Etching of Components in Chamber

Summary

- Laboratory x-ray microscopy approaches synchrotron quality
  - Achieved Brightness Comparable to 1^{st} Gen Synchrotrons
  - Demonstrated preliminary 10 sec exposure times
  - Cryo 3D Imaging and Tomography

- Future Work
  - New Zoneplates that Approach 10 nm outer zone width
  - Demonstration of more short exposures 10 – 30 sec

- Always
  - Consider full-system imaging properties before chosing optics
  - Optimum 3D resolution must be optimised for the studied object

Questions?